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# DESIGN AND USE OF A HIGH-ACCURACY NON-CONTACT ABSOLUTE THICKNESS MEASUREMENT MACHINE

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## INTRODUCTION

Many commercial metrology systems exist for making accurate surface form and roughness measurements of nominally planar parts. However, few metrology systems exist for making accurate absolute thickness measurements. At Lawrence Livermore National Laboratory there is an increasing need for absolute thickness measurements of meso-scale parts ranging in size from 1 mm to 25 mm in diameter and 2 μm to 500 μm thickness. The samples of interest in this case are nominally planar parts that require absolute thickness to be known to an accuracy of better than one micrometer.

An Absolute Thickness Measurement Machine (ATMM) has been designed and constructed to fulfill this requirement (see Figure 1). This article describes the design of the ATMM and the theory behind its operation including a detailed error budget. Other issues discussed involve errors associated with the sensors (non-linearity, and sensor resolution), development of the stepped thickness reference, thermal effects, and future upgrades. This research represents one of many issues involving meso-scale metrology currently under development at Lawrence Livermore National Laboratory.

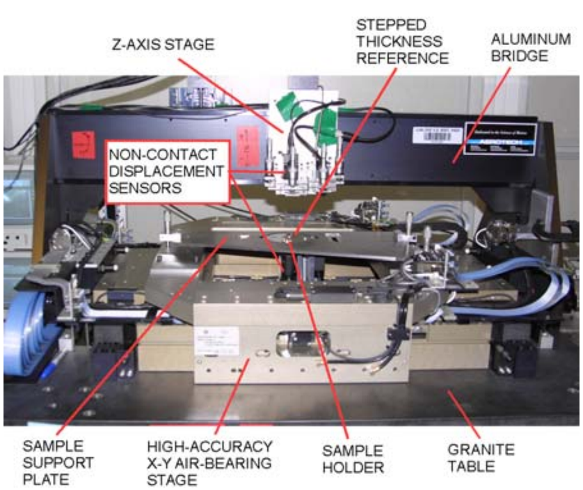


Figure 1: The Absolute Thickness Measurement Machine (ATMM)

## SYSTEM DESCRIPTION

This instrument uses two non-contact confocal laser-displacement sensors in an opposing orientation such that each sensor is simultaneously monitoring opposite sides of a sample. Calibration is done using a custom-made stepped thickness reference. Sample and reference are positioned and scanned relative to the confocal sensors by a planar air-bearing stage whose relative position is computer controlled and monitored by linear scales. Using the difference in displacement measured by each sensor and the calibrated thickness of the stepped thickness reference, thickness of planar objects can be derived over their surfaces (see Figure 2).

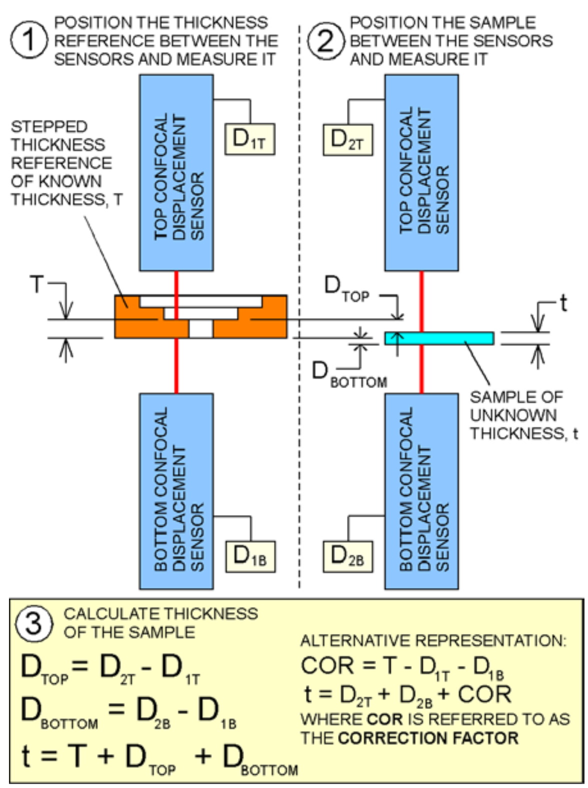


Figure 2: Calculating thickness using ATMM

## ERROR BUDGET

To achieve a thickness accuracy of better than one micrometer, all major error sources need to be accounted for and minimized. Table 1 lists the primary errors affecting thickness measurements on ATMM. As can be seen, the displacement sensors and the temperature stability of ATMM are the largest error contributors. Through the use of mechanical tilt adjustment, tilt errors can essentially be eliminated.

Table 1: ATMM error budget

| ERROR SOURCES | ERROR |
|---|---|
| Top sensor[1] | |
| Linearity/repeatability[2] | ± 300 nm |
| Noise/resolution[3] | ± 50 nm |
| Sensor tilt[4] | ± 15 nm |
| Bottom sensor[1] | |
| Linearity/repeatability[2] | ± 300 nm |
| Noise/resolution[3] | ± 50 nm |
| Sensor tilt[5] | ± 35 nm |
| Thickness reference | |
| Size tolerance[6] | ± 100 nm |
| Tilt error[7] | ~0 nm |
| Temperature stability[8] | ± 250 nm |
| Vibration stability[9] | ~0 nm |
| TOTAL[10] | ± 510 nm |

[1] Laser confocal displacement sensors.
[2] Sensors are used over the –100 to 0 μm range for all measurements.
[3] Sensor has a resolution of 100 μm; 500 measurements are averaged at each location.
[4] Sensor is aligned to within 1 degree.
[5] Sensor is aligned to within 3 degrees.
[6] Measured on LODTM
[7] Removed via tilt plate
[8] Based on a one hour measurement using our stability data
[9] Vibratory influences have not been observed
[10] Higher for transparent materials and atypical parts

Temperature stability on ATMM was measured by repeatedly monitoring the same points on the stepped thickness reference over a four-day period. Using the recorded data, the correction factor (see Figure 2 for a description of correction factor) was calculated and plotted versus time. Under ideal conditions, the correction factor should be constant. However, as can be seen in Figure 3, the correction factor fluctuates by approximately one micrometer over a full day. Comparing the recorded temperature, which varies by approximately 0.5 degrees Celsius over a day, to the correction factor, a direct correlation can be seen. Most measurements on ATMM are taken in less than 60 minutes. The largest error introduced by system instability over a 60-minute period is approximately ±250 nanometers.

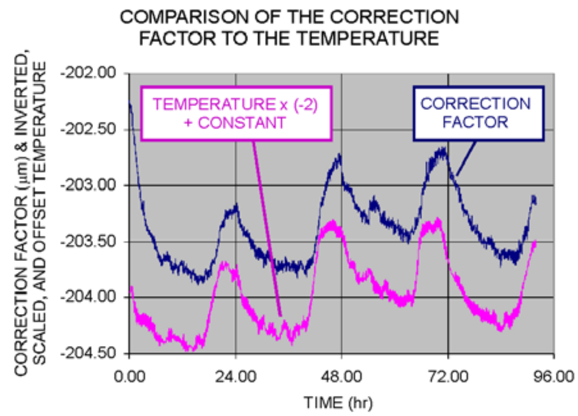


Figure 3: Relationship between temperature and system stability

The linearity/repeatability errors of the two displacement sensors were measured using LLNL's Large Optic Diamond Turning Machine (LODTM). The sensors were run through their 600-micrometer range over three bi-directional passes using a reflective metal surface affixed to the z-axis on LODTM. Each directional pass consisted of 601 one-micrometer steps; each step measurement was an average of 200 samples. Results of this test for the top displacement sensor, which took 18 hours total, are shown in Figure 4.

As can been seen, the top displacement sensor performed better in the center of its range. This was also true of the bottom displacement sensor. Since most parts to be measured on ATMM do not require use of the full range, both sensors are usually run over a 100-micrometer band in the center of their range. This results in linearity/repeatability error of approximately ± 300 nanometers for each sensor, as shown in Figure 4.

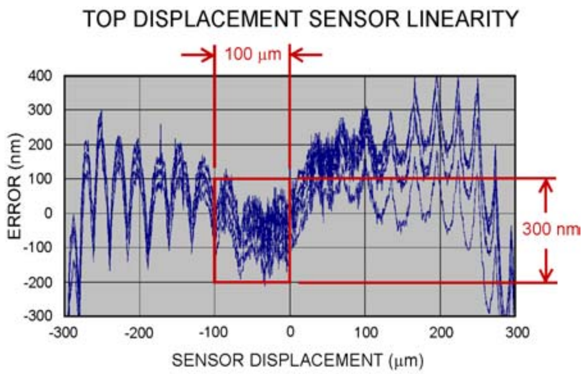


Figure 4: Linearity of top displacement sensor

The displacement sensors have a resolution of 100 nanometers. When taking data, 500 samples are averaged at each location. Using this technique, a resolution of better than ±50 nanometers appears obtainable.

**STEPPED THICKNESS REFERENCE**

An accurate thickness reference is necessary for making accurate thickness measurements. The displacement sensors are the largest error contributors due to their non-linearity; therefore, the thickness reference used should be approximately the same thickness as the sample being measured. Since ATMM measures a large range of samples varying from 2 micrometers thick up to 500 micrometers thick, a large set of different thickness references are needed. Ideally, the best solution would be to have all needed thickness references in one part. Commercial gauge blocks of 100 micrometer thickness or greater are readily available, but accurate multiple thickness references are not. A custom design stepped thickness reference was fabricated at LLNL to fulfill this need.

The stepped thickness reference used on ATMM is an annular stepped plate manufactured on a diamond turning machine out of annealed copper (see Figure 5). Starting from the center and moving radially out, the reference incrementally grows from a thickness of 25 µm to a thickness of 625 µm in 24 steps. The reference was qualified using the Large Optic Diamond Turning Machine (LODTM) equipped with an LVDT probe. The thickness reference was held down to a vacuum chuck that was faced by LODTM. Two orthogonal passes across the reference were made to measure deviation from nominal. The steps of the thickness reference are trusted to be within ±100 nanometers based on the LODTM measurements. Unfortunately, in its unreleased state, the reference is not flat due to internal stresses in the copper. This causes difficulties when trying to align the reference with the sample to be measured. The current stepped thickness reference is functional; however, an improved thickness reference is desirable. Different fabrication techniques are being investigated to minimize deflections caused by internal stresses.

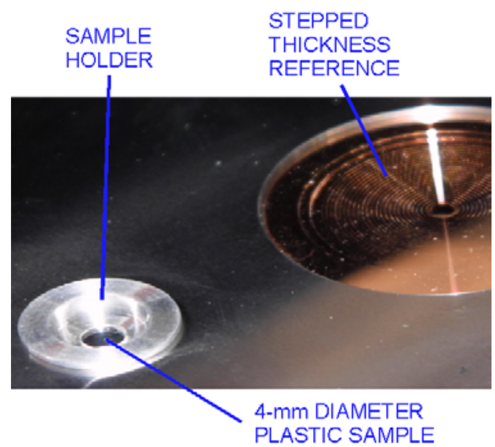


Figure 5: Stepped thickness reference

**FUTURE WORK**

Although ATMM is being used as a production measurement instrument at LLNL, many improvements can and should be made. There are plans to add more accurate displacement sensors, develop the ability to accurately measure the thickness of transparent materials, improve the user interface, and create a better thickness reference.

Currently new mounting hardware is being fabricated to support the integration of chromatic-aberration displacement sensors. These sensors should dramatically improve the accuracy of the machine. Figure 6 shows a CAD illustration of the new bottom displacement sensor and the five degree-of-freedom sensor mount.

ATMM is capable of making routine thickness measurements of smooth metal samples; however, making thickness measurements of transparent samples poses some problems. For example, when measuring transparent materials, the displacement probes interfere with each other. This can be overcome by offsetting one of the probes or by running one probe at a time. However, these changes do cause other problems. Advanced techniques for making transparent thickness measurements will be investigated in the near future.

ATMM uses a LabVIEW™ interface to control the machine motion and take measurements. There is a need to both improve the user interface to make it a technician-operated machine and to make data collection quicker through better automation. Moreover, post processing of the data needs to be streamlined to provide quick turnaround.

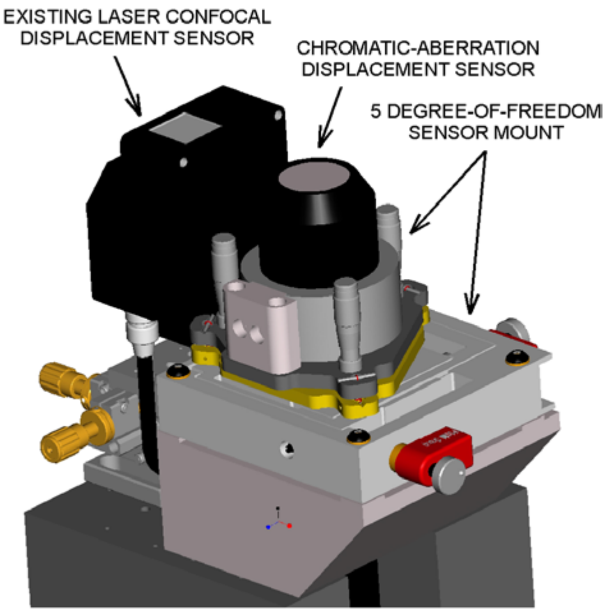


Figure 6: A new displacement sensor and mounting hardware

**CONCLUSION**

ATMM is now a functional production tool for measuring the thickness of smooth, opaque samples. It is capable of measuring thickness to better than one micrometer. Although the machine is functioning well, several upgrades are being developed.


**ACKNOWLEDGEMENTS**

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